Effective Field-Theory Tools for the LHC

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Particle Theory Seminar - Fermilab

4 March 2010

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Outline

- Introduction
- IR singularities of scattering amplitudes in non-abelian gauge theories

  Thomas Becher, MN: 0901.0722 (PRL), 0903.1126 (JHEP), 0904.1021 (PRD)
  Andrea Ferroglia, Ben Pecjak, MN, Li Lin Yang: 0907.4791 (PRL), 0908.3676 (JHEP)

- Soft gluon resummation for inclusive Higgs production

  Valentin Ahrens, Thomas Becher, MN, Li Lin Yang: 0808.3008 (PRD), 0809.4283 (EPJC)

- Threshold resummation for top-quark pair production

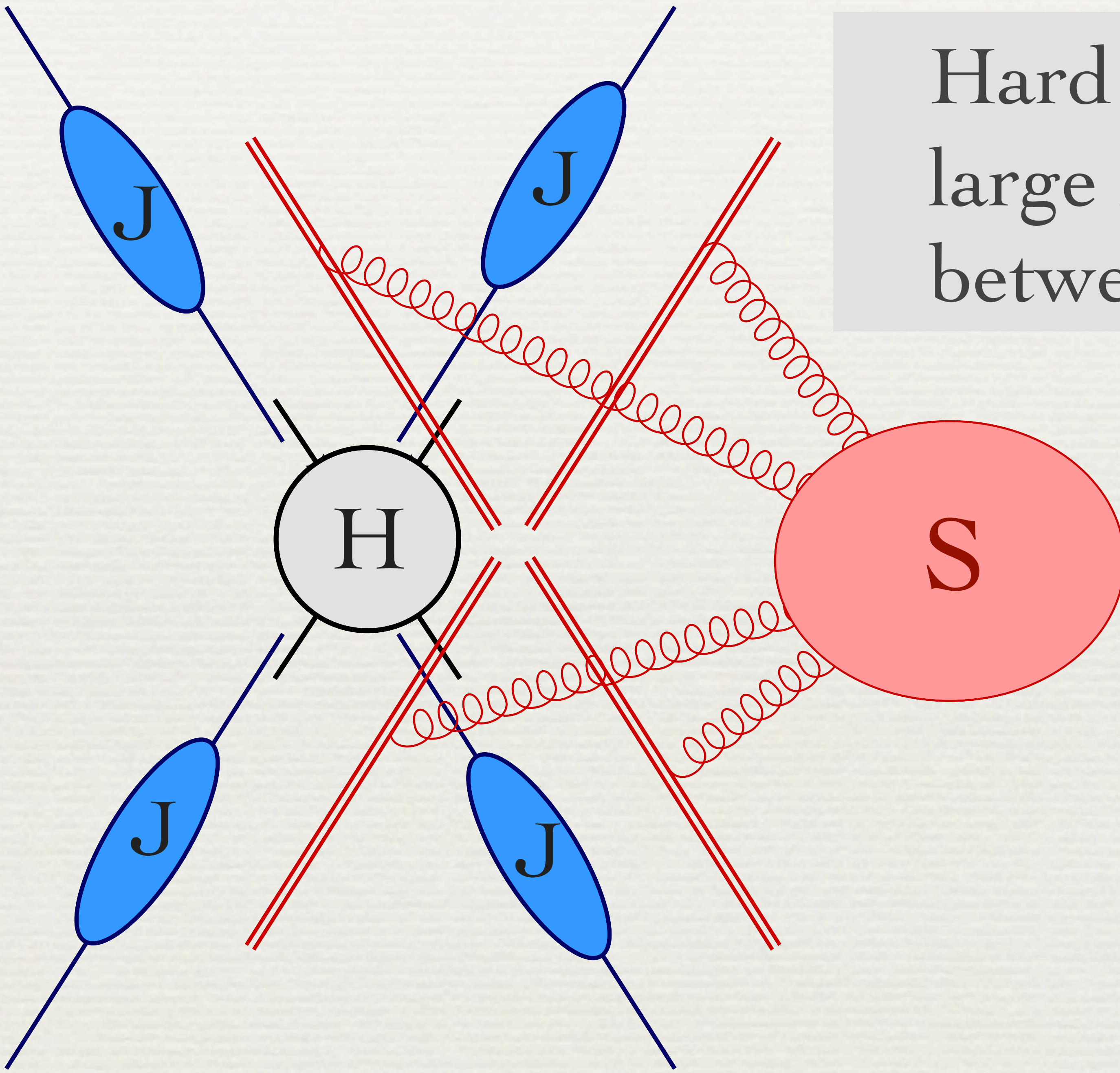
  Andrea Ferroglia, Ben Pecjak, MN, Li Lin Yang: 0912.3375 (PLB) & paper in preparation

A tale of many scales

- Collider processes characterized by many scales: s, s_{ij}, M_i, Λ_{QCD}, ...
- Large Sudakov logarithms arise, which need to be resummed (e.g. parton showers, mass effects, aspects of underlying event)
- Effective field theories provide modern, elegant approach to this problem based on scale separation (factorization theorems) and RG evolution (resummation)

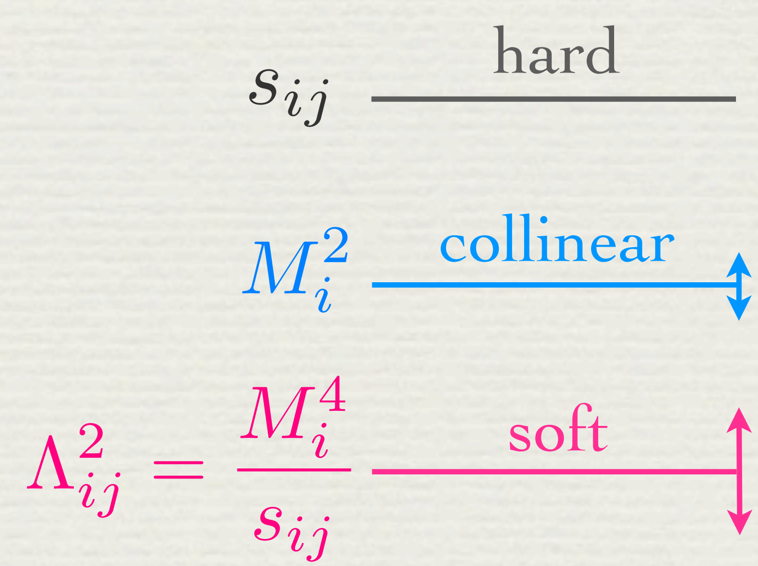
Soft-collinear factorization

Sen 1983; Kidonakis, Oderda, Sterman 1998



Hard function H depends on large momentum transfers s_{ij} between jets

Soft function S depends on scales $\Lambda_{ij}^2 = \dfrac{M_i^2 M_j^2}{-s_{ij}}$



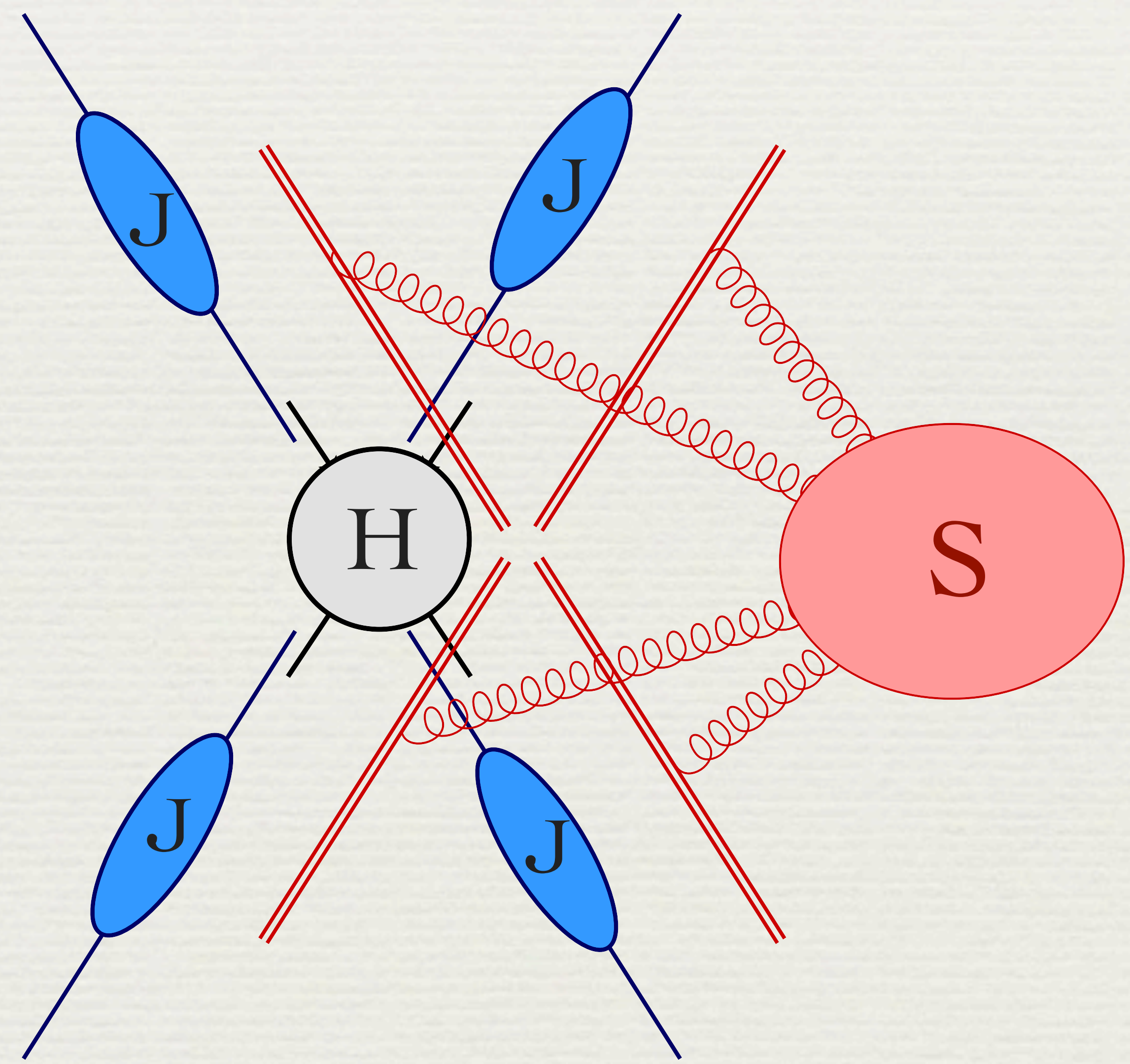
Jet functions $J_i = J_i\,(M_i^2)$

Soft-collinear factorization

- Factorize cross section:

$$d\sigma \sim H(\{s_{ij}\},\mu) \prod_i J_i(M_i^2,\mu) \otimes S(\{\Lambda_{ij}^2\},\mu)$$

- Define components in terms of field theory objects in SCET
- Resum large Sudakov logarithms directly in momentum space using RG equations

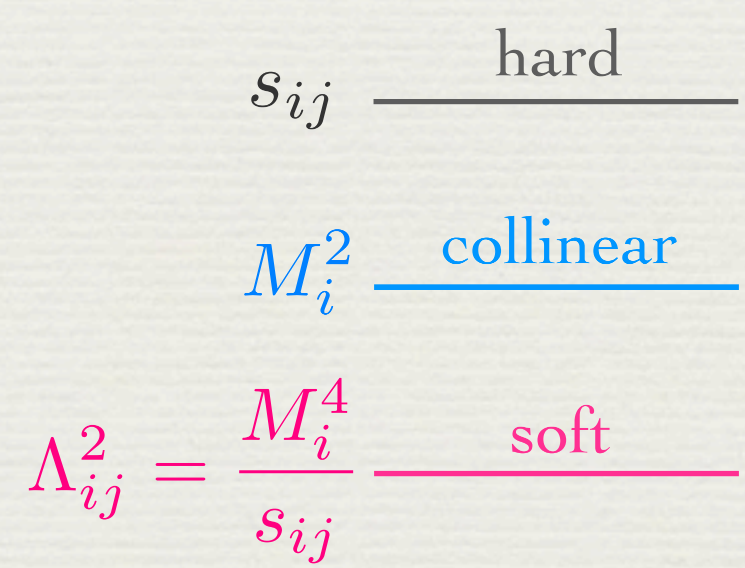


Soft-collinear effective theory (SCET)

Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke et al. 2002; ...

- Two-step matching procedure:

- Integrate out hard modes, describe collinear and soft modes by fields in SCET



- Integrate out collinear modes (if perturbative) and match onto a theory of Wilson lines

SCET for n-jet processes

- n different types of collinear quark and gluon fields (jet functions J_i), interacting only via soft gluons (soft function S)
  - $\rightarrow$ operator definitions for J_i and S
- Hard contributions ($Q \sim \sqrt{s}$) are integrated out and absorbed into Wilson coefficients:

$$\mathcal{H}_n = \sum_i \mathcal{C}_{n,i}(\mu)\, O_{n,i}^{\text{ren}}(\mu)$$

Bauer, Schwartz 2006

- Scale dependence controlled by RGE:

$$\frac{d}{d\ln\mu}\,|\mathcal{C}_n(\{\underline{p}\},\mu)\rangle = \mathbf{\Gamma}(\mu,\{\underline{p}\})\,|\mathcal{C}_n(\{\underline{p}\},\mu)\rangle$$

anomalous-dimension matrix of n-jet SCET operators

Goal: NLO+NNLL resummation

- Necessary ingredients:
  - **Hard functions:** from fixed-order results for on-shell amplitudes (but need amplitudes!)
  - **Jet functions:** from imaginary parts of two-point functions; needed at one-loop order (depend on cuts, jet definitions)
  - **Soft functions:** from matrix elements of Wilson-line operators
  - then resum logarithms using RG equations
- Yields jet cross sections (not parton rates)
- Goes beyond parton showers, which are accurate only at LL order even after matching

Evolution of hard functions

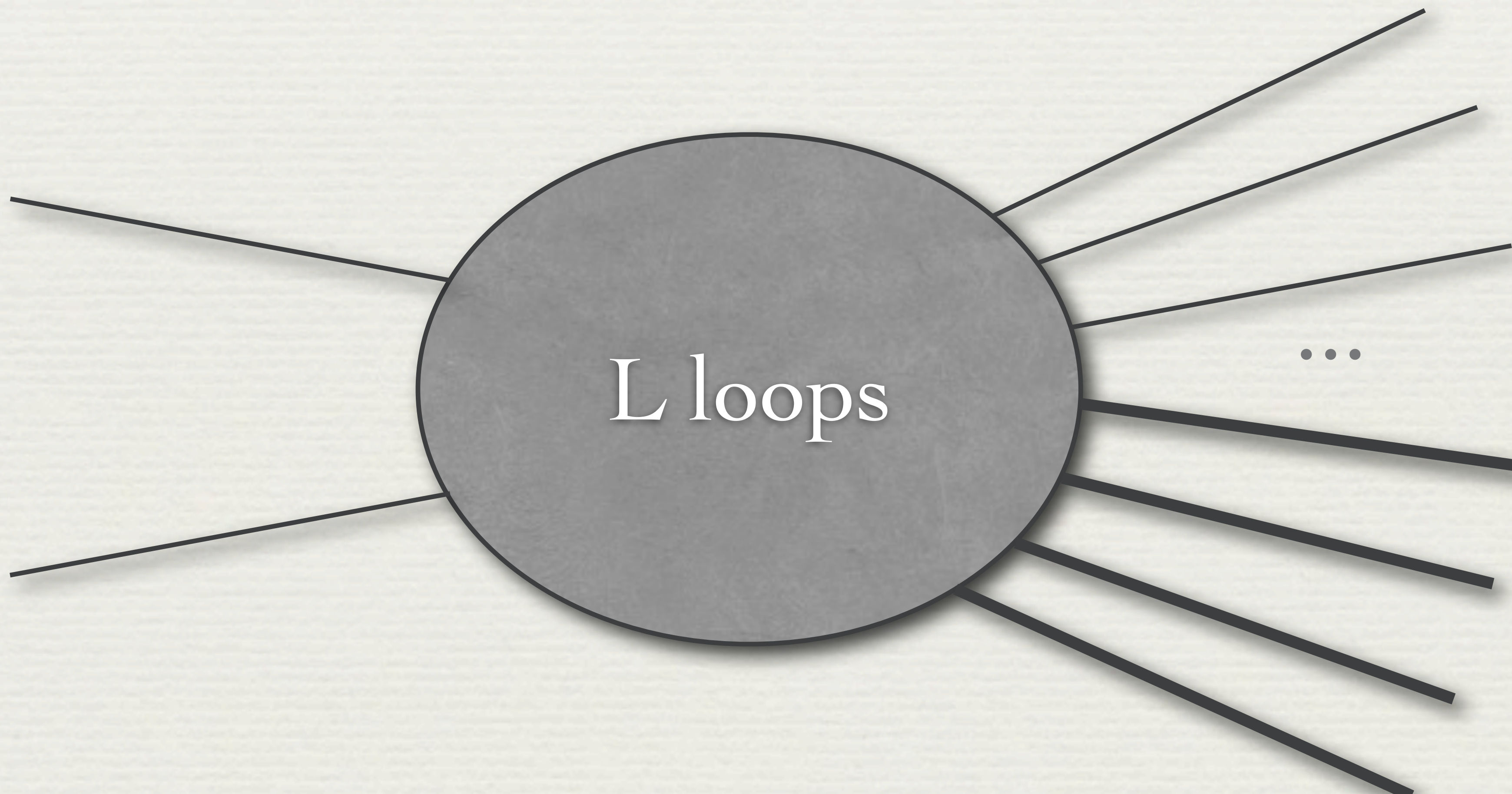
- Technically most challenging aspect besides the computation of the hard functions is their evolution, governed by anomalous-dimension matrix of n-jet operators:

$$\frac{d}{d\ln\mu}\,|\mathcal{C}_n(\{p\},\mu)\rangle = \mathbf{\Gamma}\,|\mathcal{C}_n(\{p\},\mu)\rangle$$

- We have obtained completely general, multi-loop expressions for the anomalous-dimension matrices for generic n-jet processes with both massless and massive partons

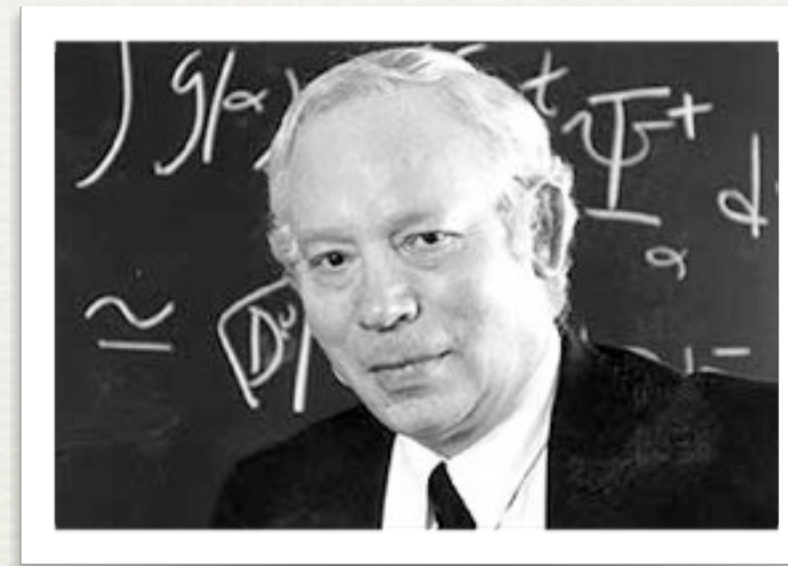
Connection with an old problem

- Same anomalous-dimension matrix governs IR poles of dimensionally regularized, on-shell parton scattering amplitudes: Becher, MN: 0901.0722

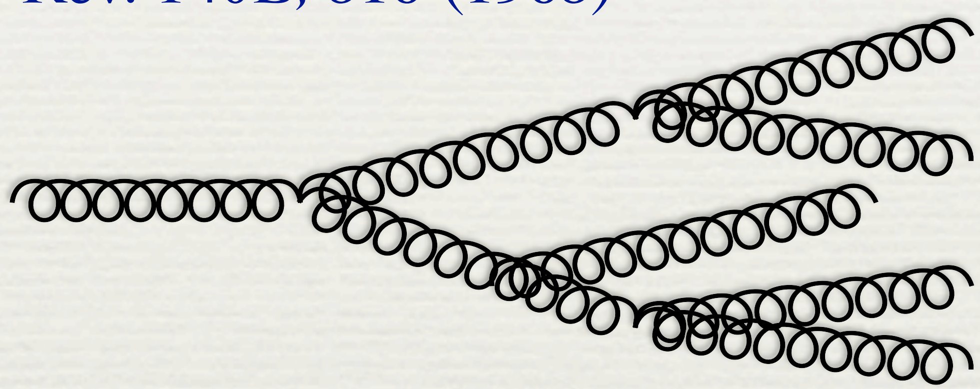


arbitrary number n of massless and massive external legs

Connection with an old problem



Difficulty of the problem already noted in pioneering work by Weinberg: Phys. Rev. 140B, 516 (1965)



"… In [Yang-Mills theory] a soft photon emitted from an external line can itself emit a pair of soft charged massless particles, which themselves emit soft photons, and so on, building up a cascade of soft massless particles each of which contributes an infra-red divergence. **The elimination of such complicated interlocking infra-red divergences would certainly be a Herculean task, and might not even be possible.**"

Connection with an old problem

- Same anomalous-dimension matrix governs IR poles of dimensionally regularized, on-shell parton scattering amplitudes: Becher, MN: 0901.0722

$$|\mathcal{M}_n(\{\underline{p}\},\mu)\rangle = \lim_{\epsilon\to 0} \boldsymbol{Z}^{-1}(\epsilon,\{\underline{p}\},\mu)\,|\mathcal{M}_n(\epsilon,\{\underline{p}\})\rangle$$

finite amplitude!

$$\boldsymbol{Z}(\epsilon,\{\underline{p}\},\mu) = \mathbf{P}\exp\left[\int_\mu^\infty \frac{d\mu'}{\mu'}\,\boldsymbol{\Gamma}(\{\underline{p}\},\mu')\right]$$

- Generalizes two-loop subtraction formula of Catani (1998) to all orders in perturbation theory [see also: Sterman, Tejeda-Yeomans 2003; Aybat, Dixon, Sterman 2006]

Constraints on Γ for amplitudes containing only massless partons

Becher, MN: 0903.1126

1. Factorization constraint on $\boldsymbol{\Gamma}$

- Operator matrix elements must evolve in the same way as hard matching coefficients, such that physical observables are scale independent
- SCET decoupling transformation then implies (with $\Lambda_{ij}^2 = \frac{M_i^2 M_j^2}{-s_{ij}}$):

trivial color structure

$$\boldsymbol{\Gamma}(s_{ij}) = \boldsymbol{\Gamma}_s(\Lambda_{ij}^2) + \sum_i \Gamma_c^i(M_i^2)\,\mathbf{1}$$

M_i dependence must cancel!

where $\Gamma_c^i(M_i^2) = -\Gamma_{\text{cusp}}^i(\alpha_s)\,\ln\frac{\mu^2}{M_i^2} + \gamma_c^i(\alpha_s)$

- $\boldsymbol{\Gamma}$ and $\boldsymbol{\Gamma}_s$ must have same color structure

1. Factorization constraint on Γ

- Independence of collinear regulators M_i requires that soft anomalous-dimension matrix is either a linear function of “cusp angles”

$$\beta_{ij} \equiv \ln \frac{\mu^2}{\Lambda_{ij}^2} = \ln \frac{\mu^2\,(-s_{ij})}{M_i^2 M_j^2}$$

or an arbitrary function of “conformal ratios”

$$\beta_{ijkl} = \beta_{ij} + \beta_{kl} - \beta_{ik} - \beta_{jl} = \ln \frac{(-s_{ij})(-s_{kl})}{(-s_{ik})(-s_{jl})}$$

which are independent of collinear scales

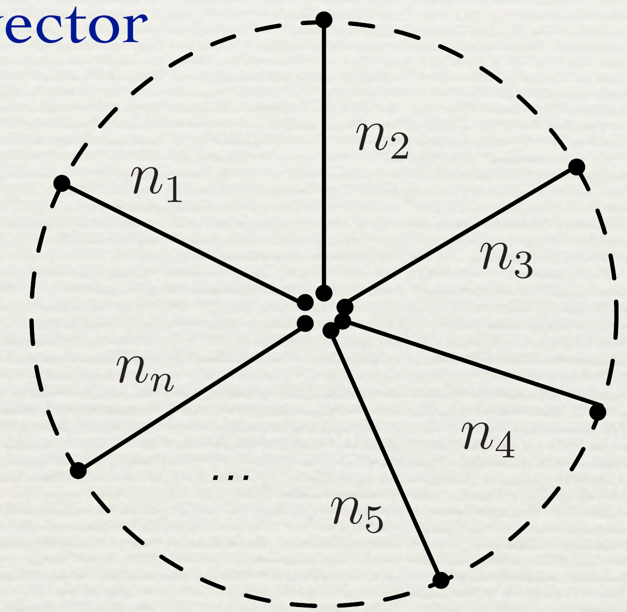
[see also: Gardi, Magnea: 0901.1091]

2. Non-abelian exponentiation

- SCET decoupling transformation removes soft interactions among collinear fields and absorbs them into soft Wilson lines

$n_i \sim p_i$ light-like reference vector

$$\boldsymbol{S}_i = \mathbf{P} \exp\left[ig \int_{-\infty}^{0} dt\, n_i \cdot A_a(t n_i)\, T_i^a \right]$$



- For n-jet operator one gets:

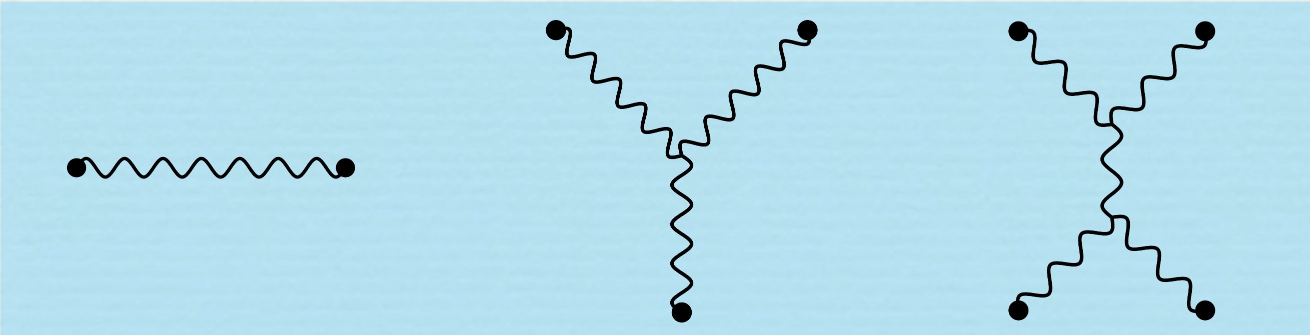
$$\mathcal{S}(\{\underline{n}\}, \mu) = \langle 0 | \boldsymbol{S}_1(0) \ldots \boldsymbol{S}_n(0) | 0 \rangle = \exp(\tilde{\mathcal{S}}(\{\underline{n}\}, \mu))$$

- Exponent $\tilde{\mathcal{S}}$ is simpler than soft operator itself

2. Non-abelian exponentiation

Gatheral 1983; Frenkel, Taylor 1984

- Virtual amplitudes in eikonal approximation are exponentials of simpler quantities, which only receive contributions from diagrams whose color weights are those of "single connected webs" (maximally non-abelian)
- Up to three loops:

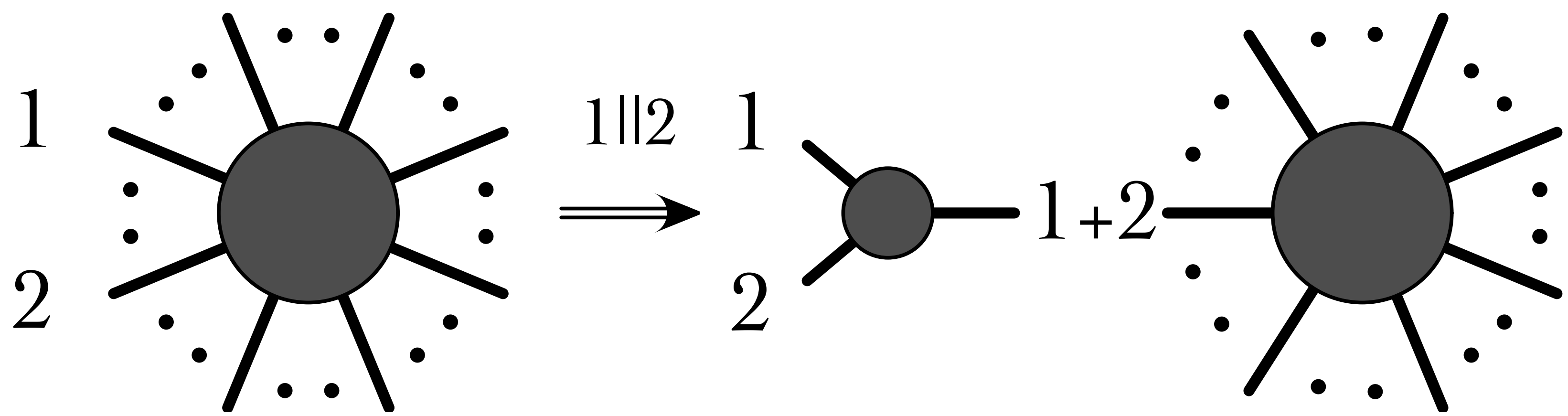


- Only these structures can contribute to the $\tilde{S}$ and hence to the soft anomalous dimension

3. Consistency with collinear limits

- When two partons become collinear, an n-parton amplitude M_n reduces to an (n-1)-parton amplitude times a splitting amplitude: Berends, Giele 1989; Mangano, Parke 1991 Kosower 1999; Catani, de Florian, Rodrigo 2003

$$|\mathcal{M}_n(\{p_1, p_2, p_3, \ldots, p_n\})\rangle = \mathbf{Sp}(\{p_1, p_2\})\, |\mathcal{M}_{n-1}(\{P, p_3, \ldots, p_n\})\rangle + \ldots$$



$$\mathbf{\Gamma}_{\rm Sp}(\{p_1, p_2\}, \mu) = \mathbf{\Gamma}(\{p_1, \ldots, p_n\}, \mu) - \mathbf{\Gamma}(\{P, p_3 \ldots, p_n\}, \mu)\Big|_{\boldsymbol{T}_P \to \boldsymbol{T}_1 + \boldsymbol{T}_2}$$

- $\mathbf{\Gamma}_{\rm Sp}$ must be independent of momenta and colors of partons 3, ..., n

Implications for $\boldsymbol{\Gamma}$

- At one- and two-loop order, this only allows for two-parton, color-dipole correlations:

Becher, MN 2009; Gardi, Magnea 2009; Bern et al. 2008

color charges

anom. dimensions, known to three-loop order

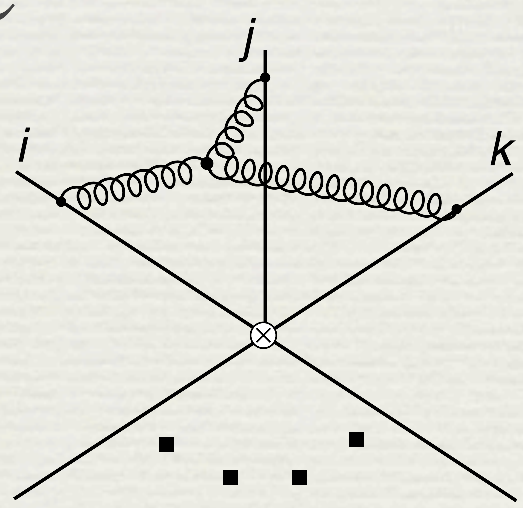
$$\boldsymbol{\Gamma}(\{\underline{p}\},\mu) = \sum_{(i,j)} \frac{\boldsymbol{T}_i \cdot \boldsymbol{T}_j}{2}\, \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s)$$

sum over pairs i≠j of partons

$(p_i + p_j)^2$

- minimal structure, reminiscent of QED
- explains cancellations observed in explicit multi-loop calculations

Aybat, Dixon, Sterman 2006; Dixon 2009



Implications for $\mathbf{\Gamma}$

- At three-loop order, a single additional 4-parton structure is allowed, involving an unknown function F that must vanish in all collinear limits:

$$\Delta\Gamma(\{\underline{p}\},\mu) = \sum_{(i,j,k,l)} f^{ade} f^{bce} \left(\boldsymbol{T}_i^a \boldsymbol{T}_j^b \boldsymbol{T}_k^c \boldsymbol{T}_l^d\right)_+ F(\beta_{ijkl}, \beta_{iklj} - \beta_{iljk})$$

- It has been conjectured that F(x,y)=0

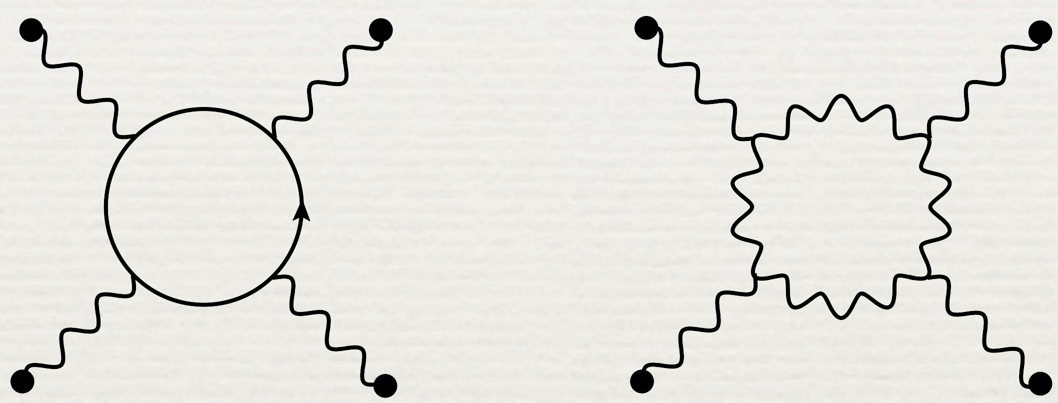
Bern et al. 2008 ; Becher, MN 2009; Gardi, Magnea 2009

- However, simple functions like $F(x,y)=x^3(x^2-y^2)$ would be consistent with all known constraints

Dixon, Gardi, Magnea: 0910.3653

Cusp logarithm at four loops

- Interesting new webs involving higher Casimir invariants first arise at four loops:



$$d_F^{abcd}\,\boldsymbol{T}_i^a\,\boldsymbol{T}_j^b\,\boldsymbol{T}_k^c\,\boldsymbol{T}_l^d = d_F^{abcd}\left(\boldsymbol{T}_i^a\,\boldsymbol{T}_j^b\,\boldsymbol{T}_k^c\,\boldsymbol{T}_l^d\right)_+$$

$$d_R^{a_1 a_2 \dots a_n} = \mathrm{tr}\Big[\,(\boldsymbol{T}_R^{a_1}\,\boldsymbol{T}_R^{a_2}\,\dots\,\boldsymbol{T}_R^{a_n})_+\Big]$$

- We have shown that they do not contribute to the coefficient of the cusp logarithm

Cusp logarithm at four loops

- Applied to the two-jet case (form factors), our constraints thus imply Casimir scaling of the cusp anomalous dimension to four-loop order:

$$\frac{\Gamma^q_{\text{cusp}}(\alpha_s)}{C_F} = \frac{\Gamma^g_{\text{cusp}}(\alpha_s)}{C_A} = \gamma_{\text{cusp}}(\alpha_s)$$

- Checked explicitly at three loops Moch, Vermaseren, Vogt 2004
- At odds with expectations from AdS/CFT correspondence (strong-coupling limit)
- Presumably not a real conflict ... Armoni 2006 Alday, Maldacena 2007

Extension to massive partons

Heavy particles

- Have extended our analysis to amplitudes which contain massive partons Becher, MN: 0904.1021
- Effective theory is a combination of HQET (heavy partons) and SCET (massless partons)
- Constraints from soft-collinear factorization and collinear limits no longer apply
- For the purely massive case, all structures allowed by non-abelian exponentiation at a given order will be present!

Anomalous dimension to two loops

- General result:

extracetd from:
Korchemsky, Radyushkin 1987

$$\boldsymbol{\Gamma}(\{\underline{p}\},\{\underline{m}\},\mu) = \sum_{(i,j)} \frac{\boldsymbol{T}_i\cdot\boldsymbol{T}_j}{2}\,\gamma_{\text{cusp}}(\alpha_s)\,\ln\frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s)$$

massless partons

$$\boxed{\begin{aligned}&-\sum_{(I,J)} \frac{\boldsymbol{T}_I\cdot\boldsymbol{T}_J}{2}\,\gamma_{\text{cusp}}(\beta_{IJ},\alpha_s) + \sum_I \gamma^I(\alpha_s) + \sum_{I,j} \boldsymbol{T}_I\cdot\boldsymbol{T}_j\,\gamma_{\text{cusp}}(\alpha_s)\,\ln\frac{m_I\mu}{-s_{Ij}}\\ &+\sum_{(I,J,K)} if^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_K^c\,F_1(\beta_{IJ},\beta_{JK},\beta_{KI})\\ &+\sum_{(I,J)}\sum_k if^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_k^c\,f_2\Big(\beta_{IJ},\ln\frac{-\sigma_{Jk}\,v_J\cdot p_k}{-\sigma_{Ik}\,v_I\cdot p_k}\Big) + \mathcal{O}(\alpha_s^3)\,.\end{aligned}}$$

massive partons

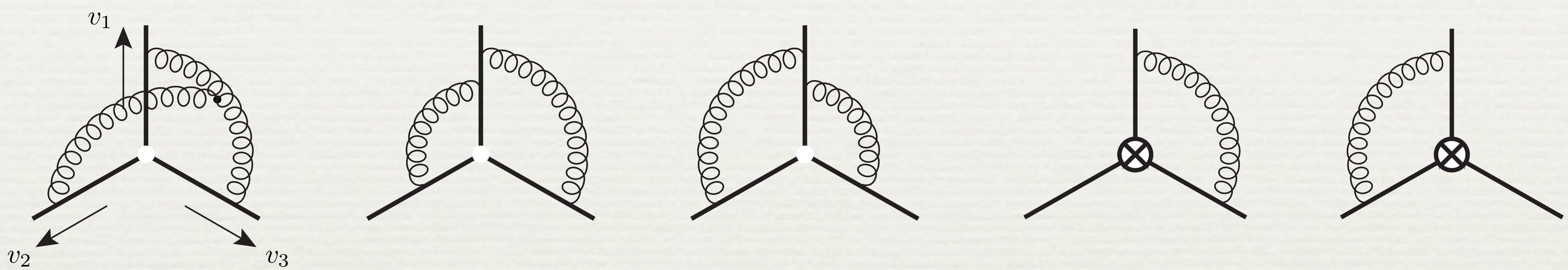
new!

- Generalizes structure found for massless case
- Novel three-parton terms appear at two-loop order Mitov, Sterman, Sung: 0903.3241; Becher, MN: 0904.1021

Calculation of three-parton terms

Ferroglia, MN, Pecjak, Yang: 0907.4791, 0908.3676

- Relevant two-loop diagrams:



- Surprisingly simple answer:

anti-symmetric in heavy-parton indices

$$F_1(\beta_{12},\beta_{23},\beta_{31}) = \frac{1}{3}\sum_{I,J,K} \epsilon_{IJK}\, \frac{\alpha_s}{4\pi} \boxed{g(\beta_{IJ})}\, \gamma_{\rm cusp}(\beta_{KI},\alpha_s)$$

$$f_2\Big(\beta_{12}, \ln\frac{-\sigma_{23}\, v_2\cdot p_3}{-\sigma_{13}\, v_1\cdot p_3}\Big) = -\frac{\alpha_s}{4\pi} \boxed{g(\beta_{12})}\, \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{-\sigma_{23}\, v_2\cdot p_3}{-\sigma_{13}\, v_1\cdot p_3}$$

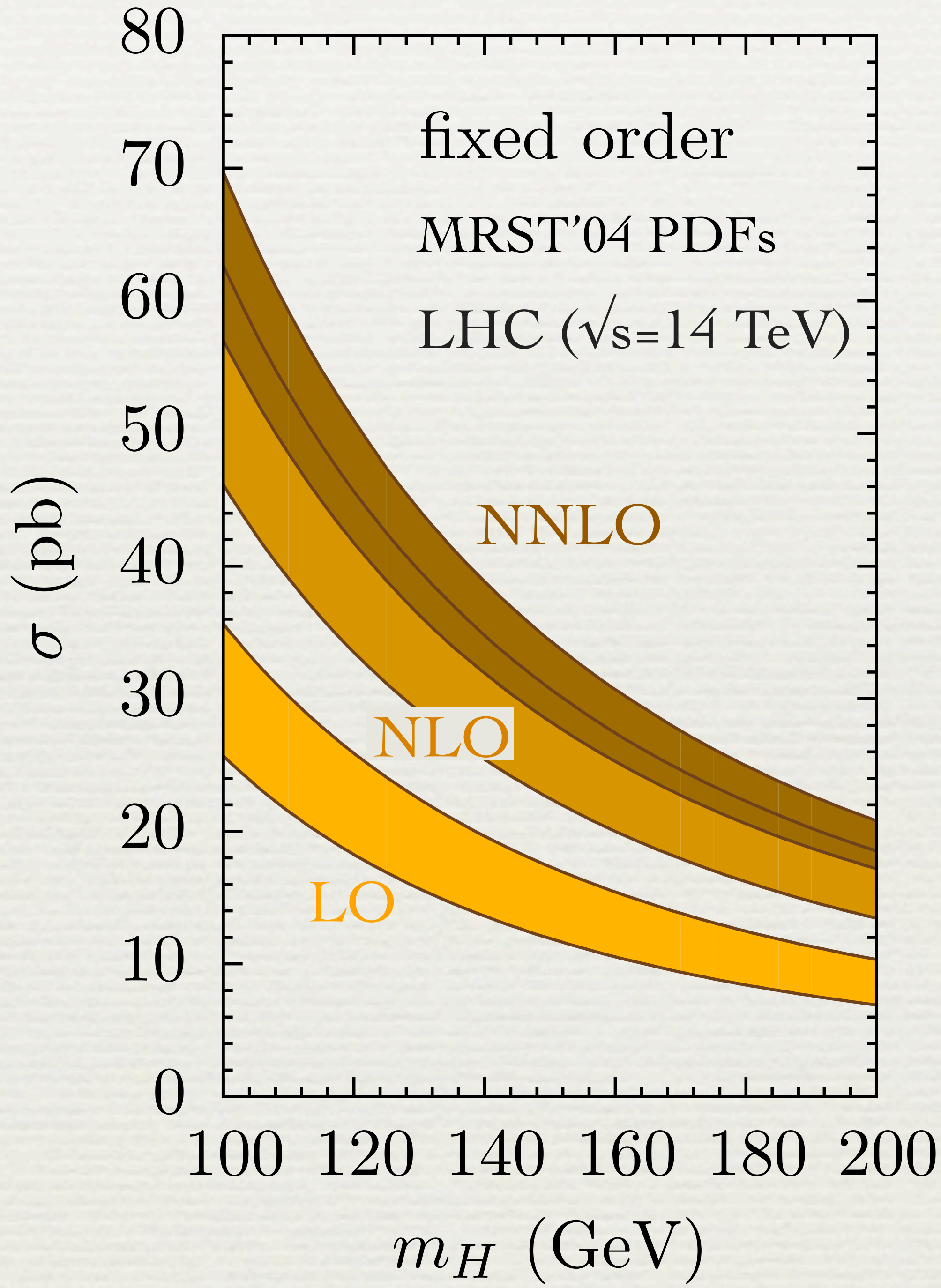
with:

$$g(\beta) = \coth\beta \left[\beta^2 + 2\beta\,\ln(1-e^{-2\beta}) - \mathrm{Li}_2(e^{-2\beta}) + \frac{\pi^2}{6}\right] - \beta^2 - \frac{\pi^2}{6}$$

EFT-based resummation for inclusive Higgs production at Tevatron and LHC

Ahrens, Becher, MN, Yang: 0808.5008, 0809.4283

Large higher-order corrections



Harlander, Kilgore 2002; Anastasiou, Melnikov 2002
Ravindran, Smith, van Neerven 2003

- Corrections are large:
  70% at NLO + 30% at NNLO [130% and 80% if PDFs and α_s are held fixed]
- Only C_{gg} contains leading singular terms, which give 90% of NLO and 94% of NNLO correction
- Contributions of C_{qg} and C_{qq} are small: -1% and -8% of the NLO correction

Effective theory analysis

- Separate contributions associated with different scales, turning a multi-scale problems into a series of single-scale problems
- Evaluate each contribution at its natural scale, leading to improved perturbative behavior
- Use renormalization group to evolve contributions to an arbitrary factorization scale, thereby exponentiating (resumming) large corrections

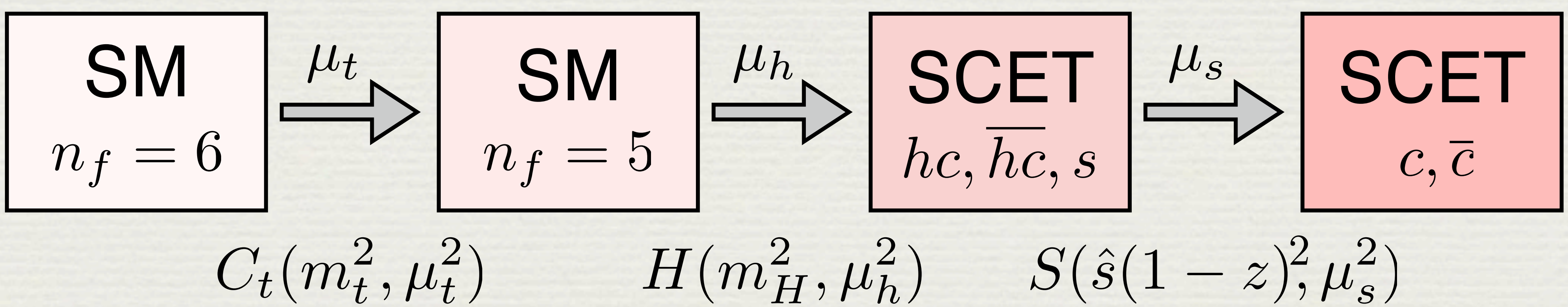
When this is done consistently, large K-factors should never arise, since no large perturbative corrections should be left unexponentiated!

Scale hierarchy

- Will analyze the Higgs cross section assuming the scale hierarchy ($z = M_H^2/\hat{s}$)

$$2m_t \gg m_H \sim \sqrt{\hat{s}} \gg \sqrt{\hat{s}}(1-z) \gg \Lambda_{\mathrm{QCD}}$$

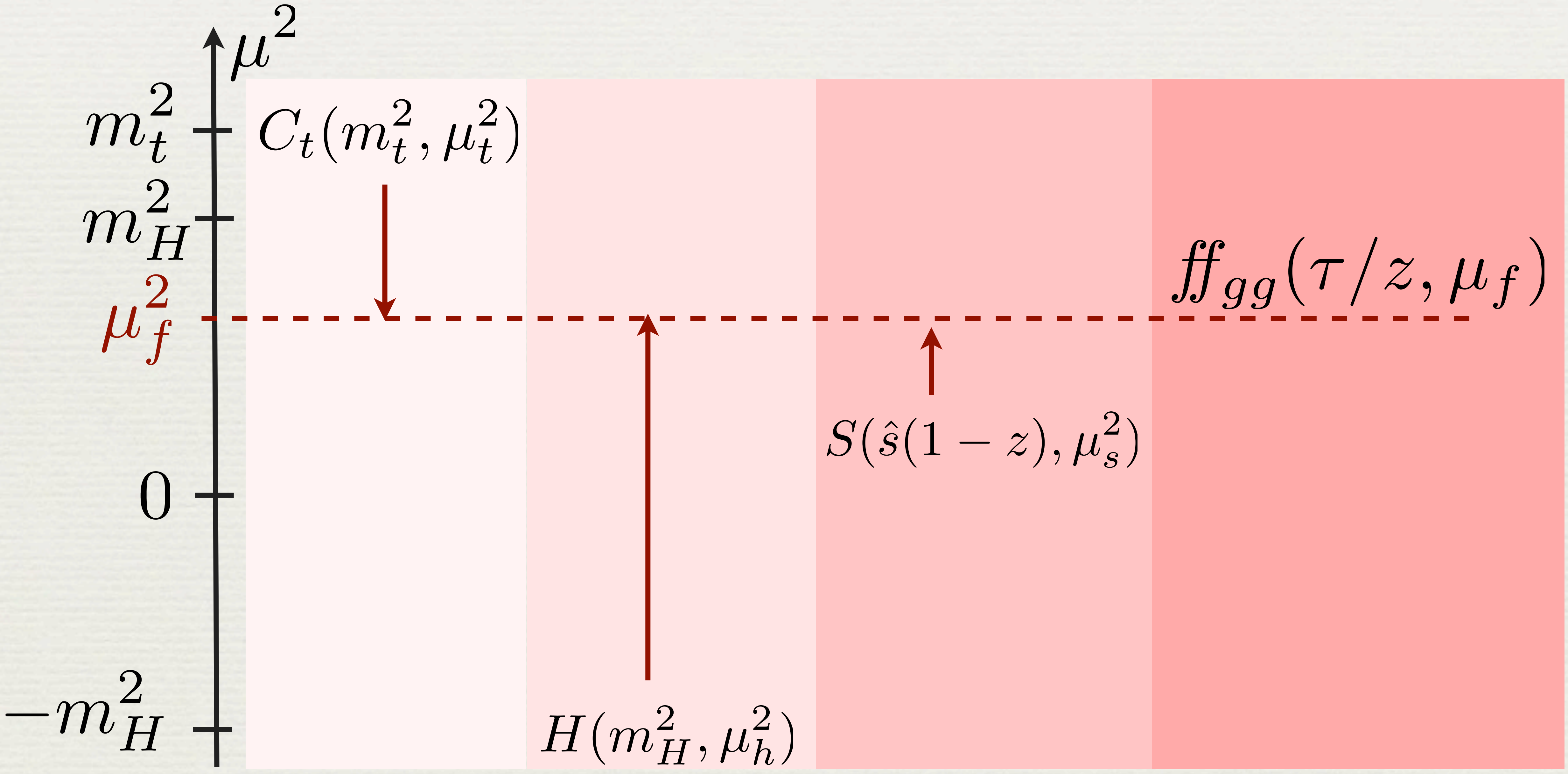
- Treating one scale at a time leads to a sequence of effective theories:



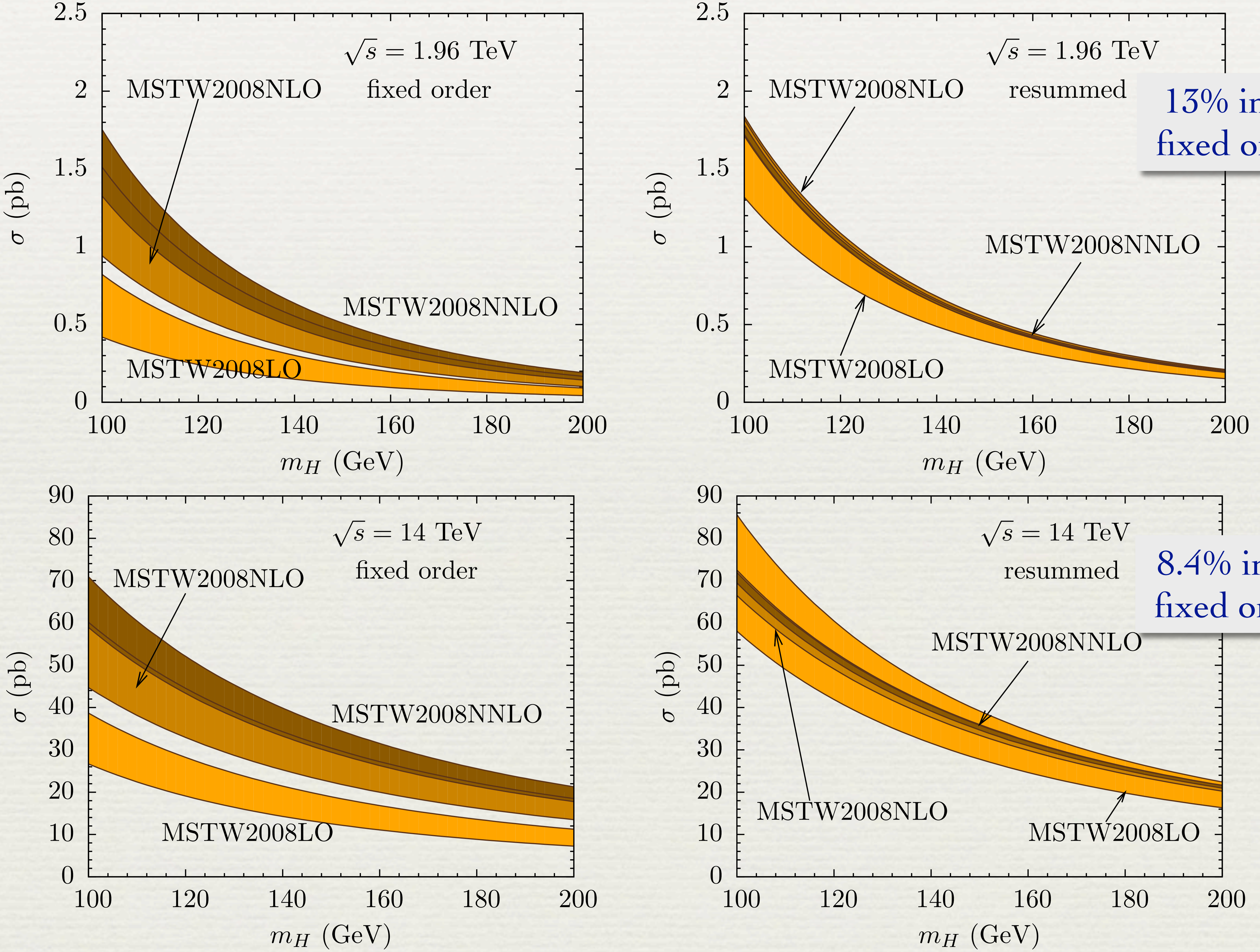
- Effects associated with each scale absorbed into matching coefficients

Scale hierarchy

- Evaluate each part at its characteristic scale and evolve to a common scale using RGEs:

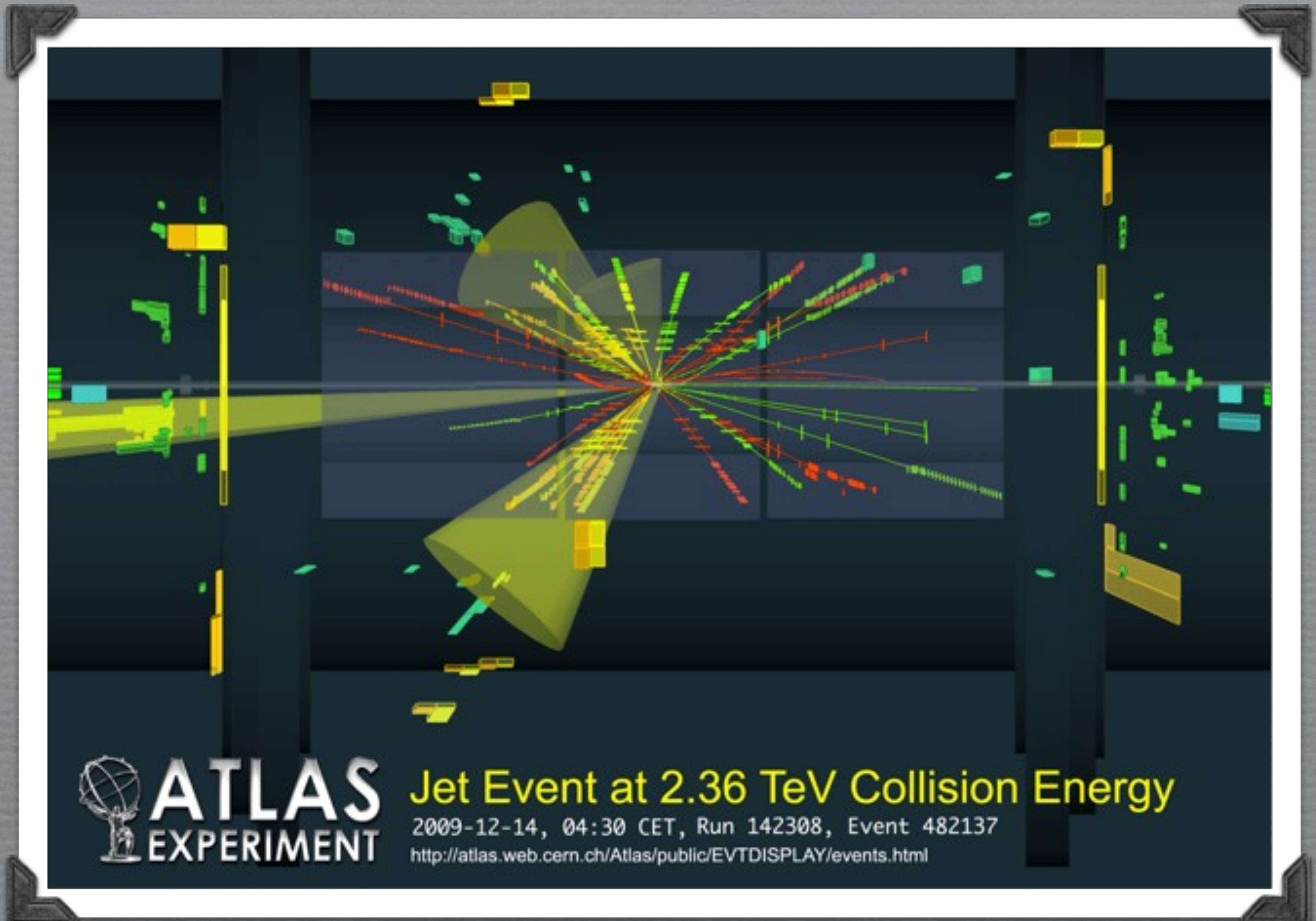


Cross section predictions



13% increase over fixed order NNLO

8.4% increase over fixed order NNLO



EFT-based threshold expansion at $O(\alpha_s^4)$ for top-quark pair production

Ahrens, Ferroglia, MN, Pecjak, Yang: 0912.3375 & in preparation

State of the art

- Fixed-order NLO calculations:
  - total cross section: Nason, Dawson, Ellis 1988; Beenakker et al. 1989
  - differential: Nason, Dawson, Ellis 1989; Mangano, Nason, Ridolfi 1992; Frixione, Mangano, Nason, Ridolfi 1995
  - A_{FB}^t: Kühn, Rodrigo 1998
- Fixed-order NNLO calculations:
  - none exist!
  - "leading terms" (enhanced near threshold) for total cross section: Beneke, Falgari, Schwinn 2009; Czakon, Mitov, Sterman 2009
  - "leading terms" for distributions, A_{FB}^t **this work!**

State of the art

- Threshold resummation at NLL:
  - total cross section: Bonciani, Catani, Mangano, Nason 1998; Berger, Contopanagos 1995; Kidonakis, Laenen, Moch, Vogt 2001
  - distributions: Kidonakis, Vogt 2003; Banfi, Laenen 2005
  - A_{FB}^{t}: Almeida, Sterman, Vogelsang 2008
- Resummation at NNLL+NLO matching:
  - total cross section: Beneke, Falgari, Schwinn 2009; Czakon, Mitov, Sterman 2009
  - distributions: **this work!**

Top-pair production: IR poles

Ferroglia, MN, Pecjak, Yang: 0908.3676

- Anomalous-dimension matrices in s-channel singlet-octet basis for $q\bar{q}, gg \to t\bar{t}$ channels:

$$\begin{aligned}
\boldsymbol{\Gamma}_{q\bar{q}} &= \left[C_F\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{-s}{\mu^2} + C_F\,\gamma_{\rm cusp}(\beta_{34},\alpha_s) + 2\gamma^q(\alpha_s) + 2\gamma^Q(\alpha_s) \right] \mathbf{1} \\
&\quad + \frac{N}{2} \left[\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{(-s_{13})(-s_{24})}{(-s)\,m_t^2} - \gamma_{\rm cusp}(\beta_{34},\alpha_s) \right] \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \\
&\quad + \gamma_{\rm cusp}(\alpha_s)\,\ln\frac{(-s_{13})(-s_{24})}{(-s_{14})(-s_{23})} \left[\begin{pmatrix} 0 & \frac{C_F}{2N} \\ 1 & -\frac{1}{N} \end{pmatrix} + \frac{\alpha_s}{4\pi}\,g(\beta_{34}) \begin{pmatrix} 0 & \frac{C_F}{2} \\ -N & 0 \end{pmatrix} \right] + \mathcal{O}(\alpha_s^3)
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\Gamma}_{gg} &= \left[N\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{-s}{\mu^2} + C_F\,\gamma_{\rm cusp}(\beta_{34},\alpha_s) + 2\gamma^g(\alpha_s) + 2\gamma^Q(\alpha_s) \right] \mathbf{1} \\
&\quad + \frac{N}{2} \left[\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{(-s_{13})(-s_{24})}{(-s)\,m_t^2} - \gamma_{\rm cusp}(\beta_{34},\alpha_s) \right] \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (55) \\
&\quad + \gamma_{\rm cusp}(\alpha_s)\,\ln\frac{(-s_{13})(-s_{24})}{(-s_{14})(-s_{23})} \left[\begin{pmatrix} 0 & \frac{1}{2} & 0 \\ 1 & -\frac{N}{4} & \frac{N^2-4}{4N} \\ 0 & \frac{N}{4} & -\frac{N}{4} \end{pmatrix} + \frac{\alpha_s}{4\pi}\,g(\beta_{34}) \begin{pmatrix} 0 & \frac{N}{2} & 0 \\ -N & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] + \mathcal{O}(\alpha_s^3)\,.
\end{aligned}$$

Top-pair production: IR poles

- Can use these results to predict all IR poles in virtual 2-loop amplitudes in analytic form, e.g. for gg channel (were not known before):

$$2\,\mathrm{Re}\,\langle \mathcal{M}^{(0)} | \mathcal{M}^{(2)} \rangle_{gg} = (N^2-1)\Bigg(N^3 A^g + N\,B^g + \frac{1}{N}\,C^g + \frac{1}{N^3}\,D^g$$

$$+ N^2 n_l\,E^g_l + N^2 n_h\,E^g_h + n_l\,F^g_l + n_h\,F^g_h + \frac{n_l}{N^2}\,G^g_l + \frac{n_h}{N^2}\,G^g_h$$

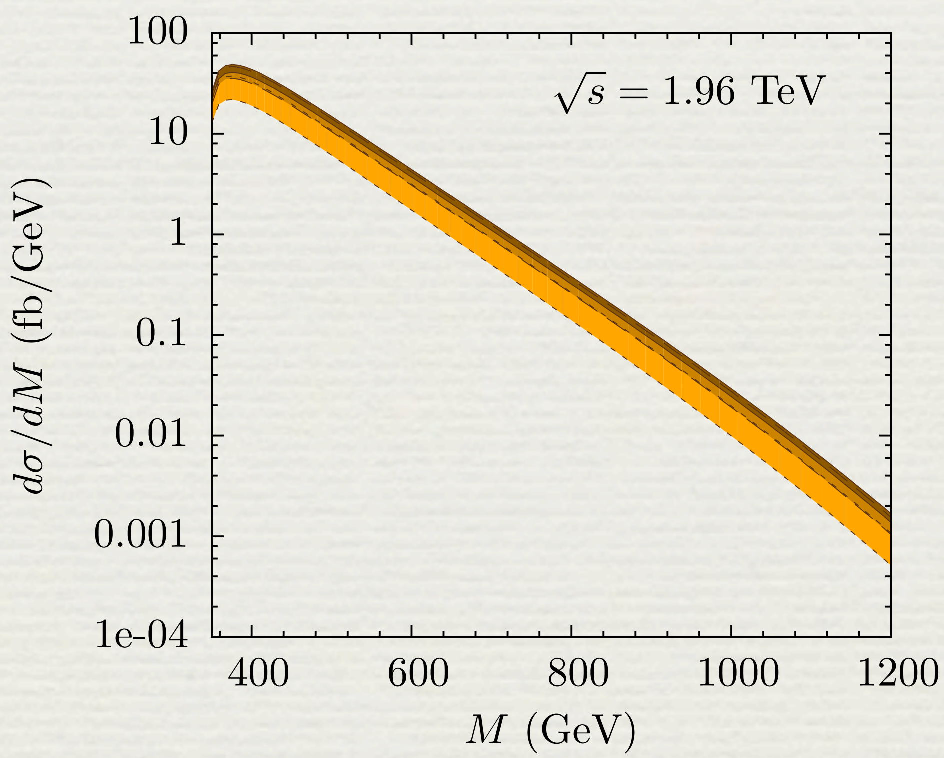
$$+ N n_l^2 H^g_l + N n_l n_h\,H^g_{lh} + N n_h^2 H^g_h + \frac{n_l^2}{N}\,I^g_l + \frac{n_l n_h}{N}\,I^g_{lh} + \frac{n_h^2}{N}\,I^g_h \Bigg)$$

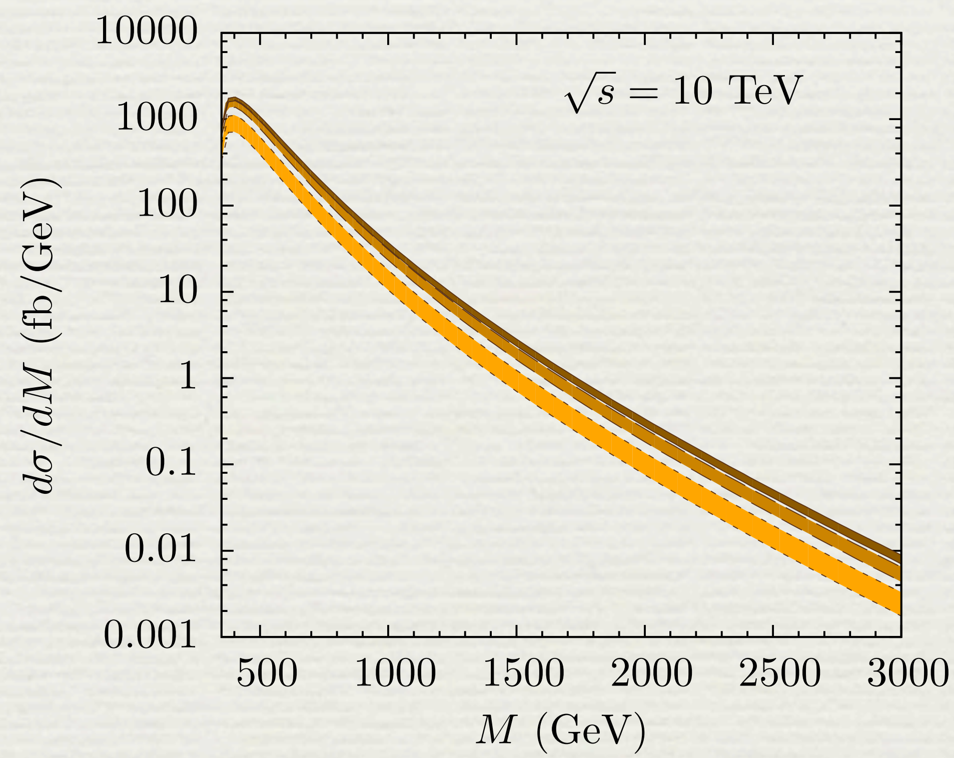
	ϵ^{-4}	ϵ^{-3}	ϵ^{-2}	ϵ^{-1}
A^g	10.749	18.694	−156.82	262.15
B^g	−21.286	−55.990	−235.04	1459.8
C^g		−6.1991	−68.703	−268.11
D^g			94.087	−130.96
E^g_l		−12.541	18.207	27.957
E^g_h			0.012908	11.793
F^g_l		24.834	−26.609	−50.754
F^g_h			0.0	−23.329
G^g_l			3.0995	67.043
G^g_h				0.0
H^g_l			2.3888	−5.4520
H^g_{lh}				−0.0043025
H^g_h				
I^g_l			−4.7302	10.810
I^g_{lh}				0.0
I^g_h				

- Basis for NNLL threshold resummation for tt production ($d\sigma_{tt}/dM_{tt}$ as well as σ_{tt}) at LHC/Tevatron

Leading threshold terms at NNLO

- Knowledge of IR singularities allows one to deduce the leading terms near the partonic threshold for the $p\overset{(-)}{p} \to t\bar{t}$ invariant mass distribution at $O(\alpha_s^4)$: Ahrens, Ferroglia, MN, Pecjak, Yang: 0912.3375





NNLO
(partial)

NLO

LO

- Widths of bands from $M/2 < \mu < 2M$

Leading threshold terms at NNLO

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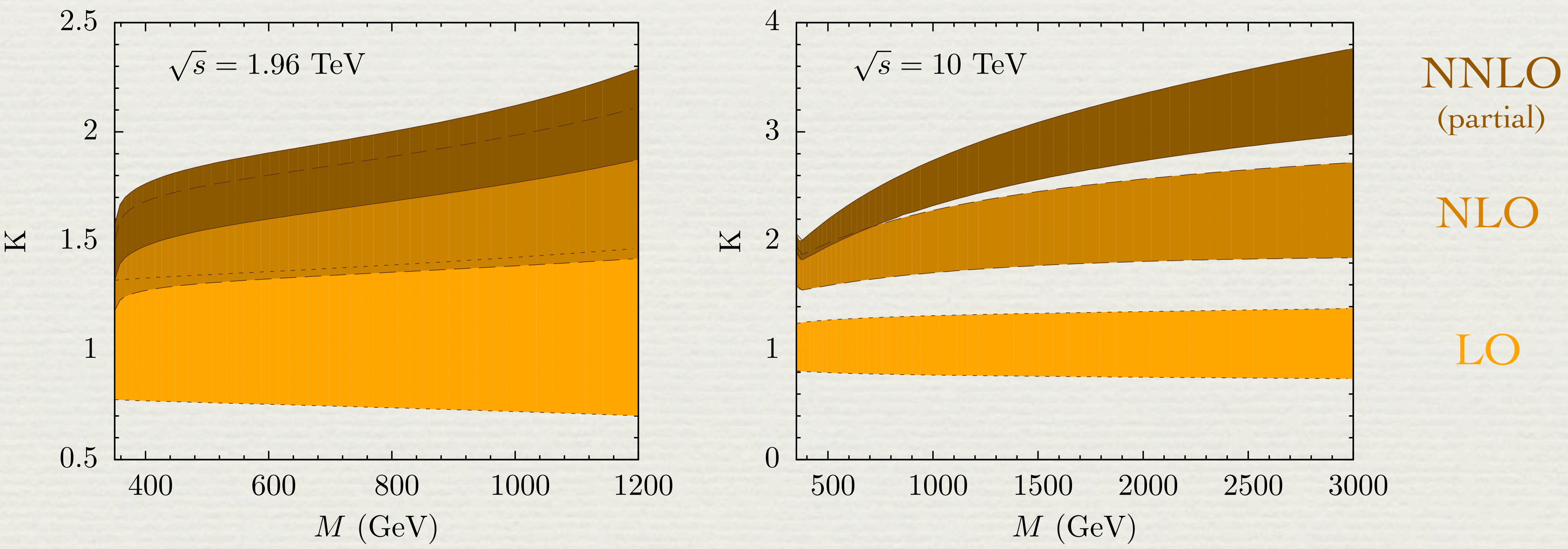

- Widths of bands $M/2 < \mu < 2M$

Threshold resummation at NNLL

Ahrens, Ferroglia, MN, Pecjak, Yang: in prep.

- Resum, lower LHC energy, change colors...

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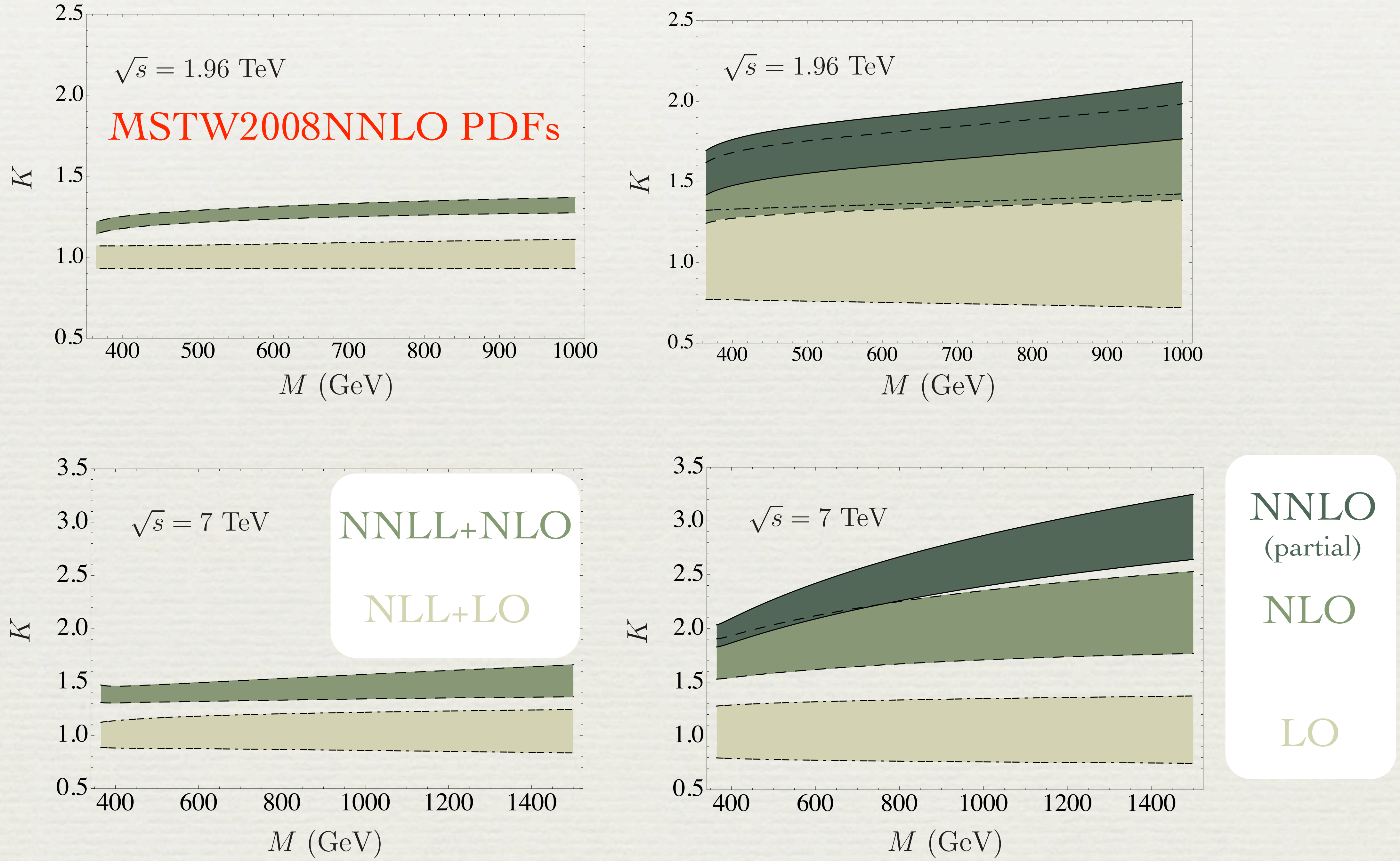

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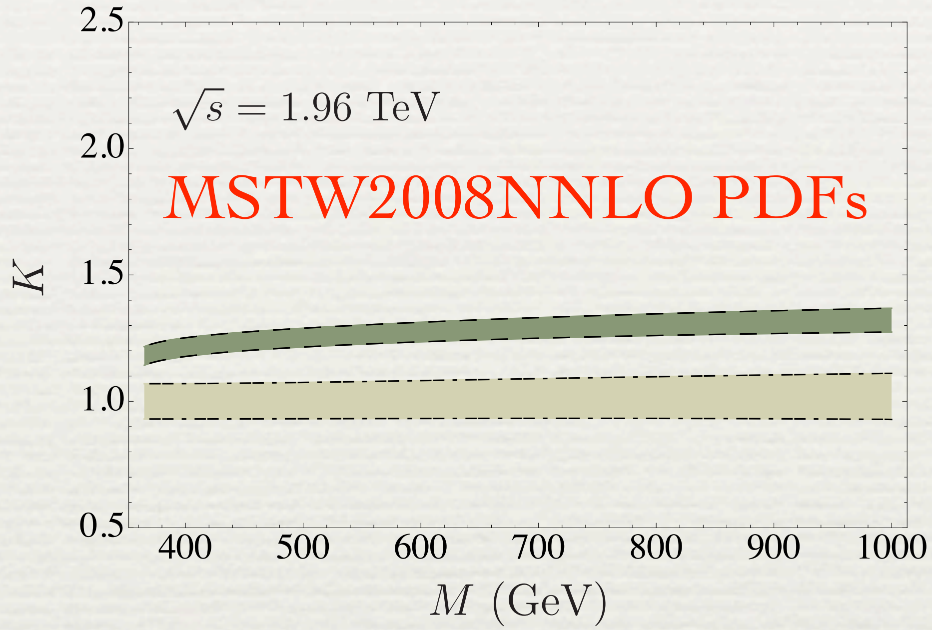
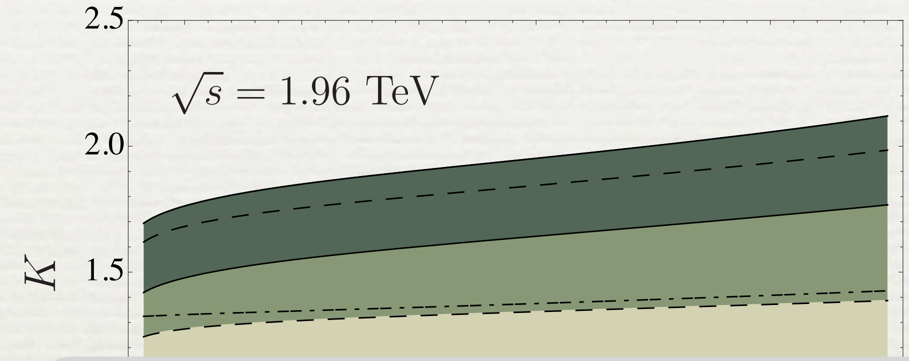
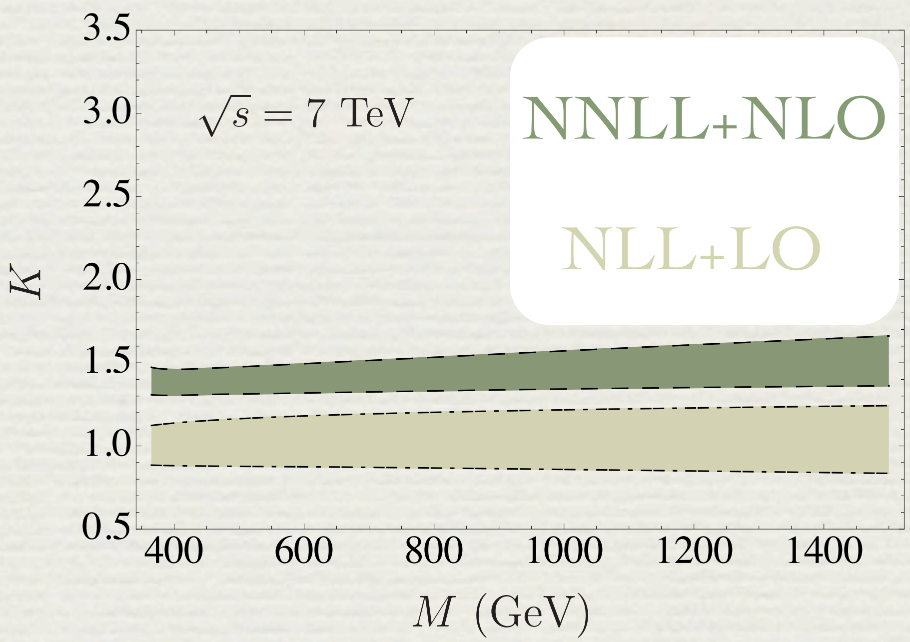
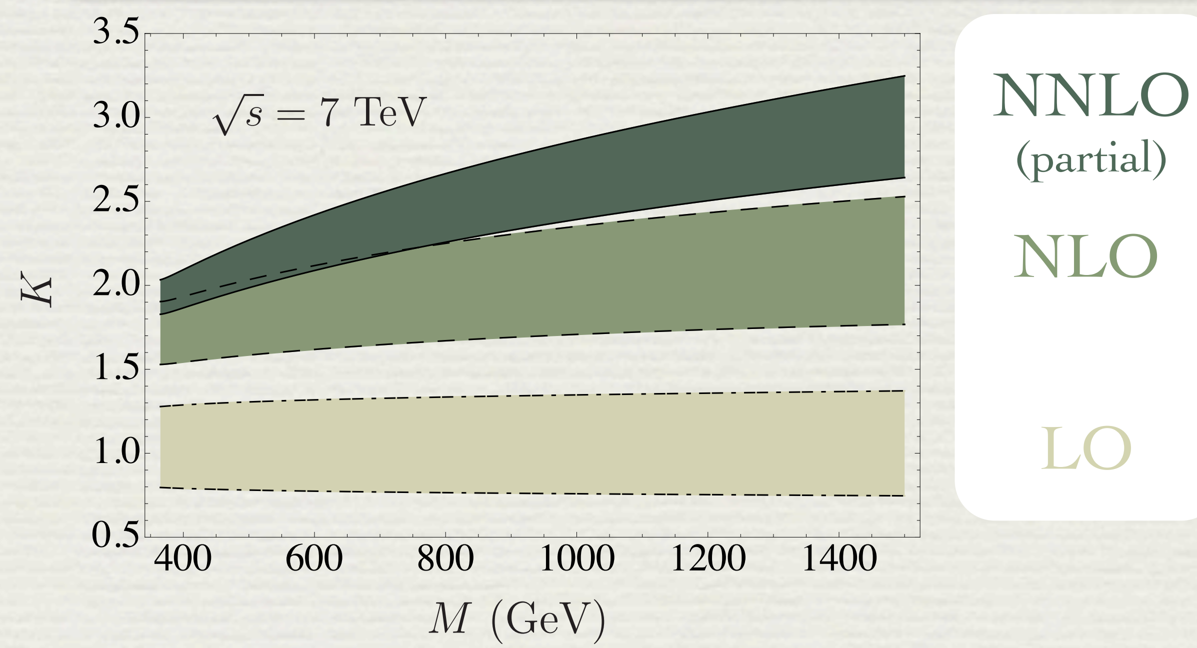




RG-impr. PT	log accuracy	Γ_{cusp}	γ^h, γ^ϕ	$\boldsymbol{H}$, $\tilde{\boldsymbol{s}}$
LO	NLL	2-loop	1-loop	tree-level
NLO	NNLL	3-loop	2-loop	1-loop





Threshold resummation at NNLL

Ahrens, Ferroglia, MN, Pecjak, Yang: in prep.

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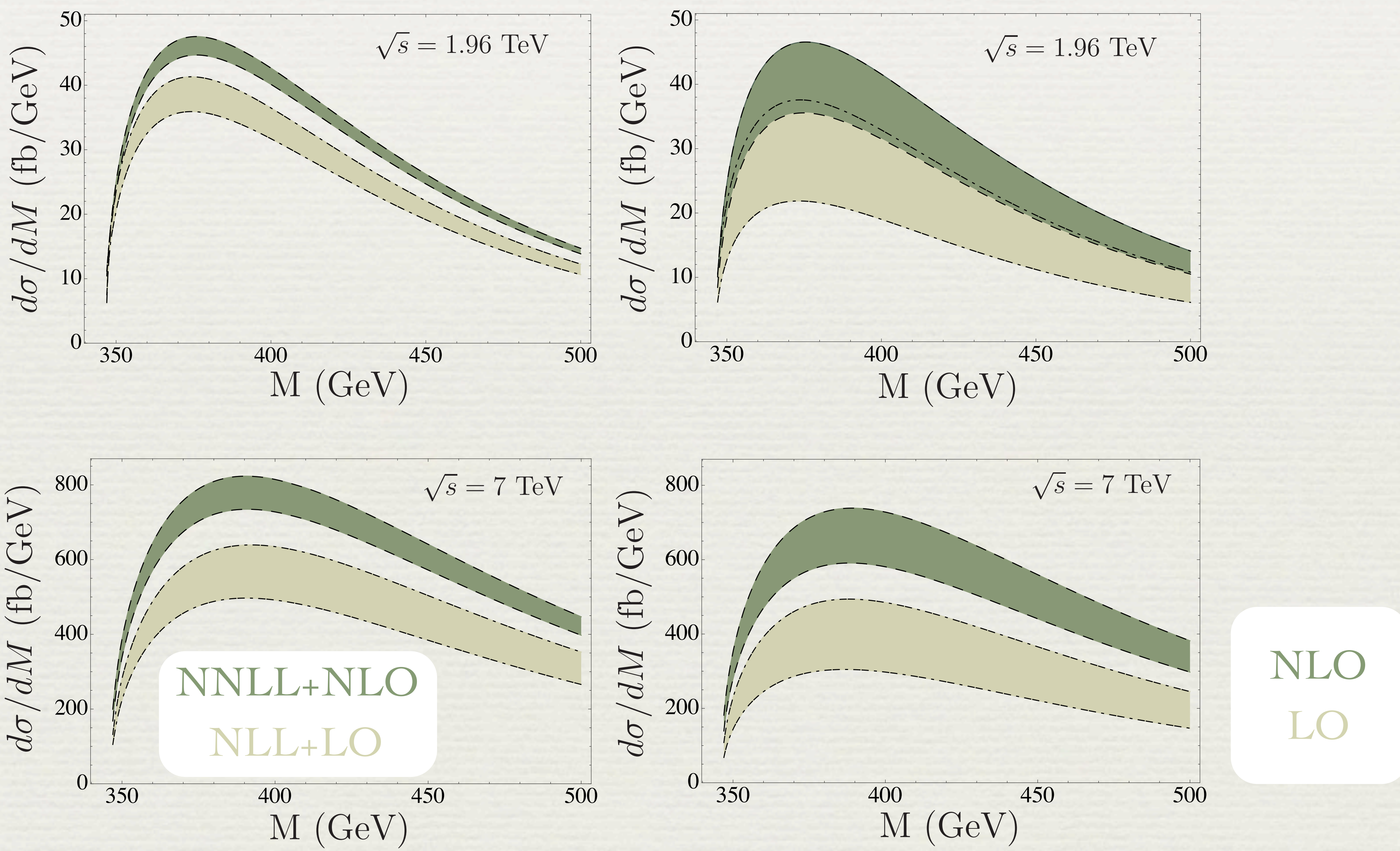
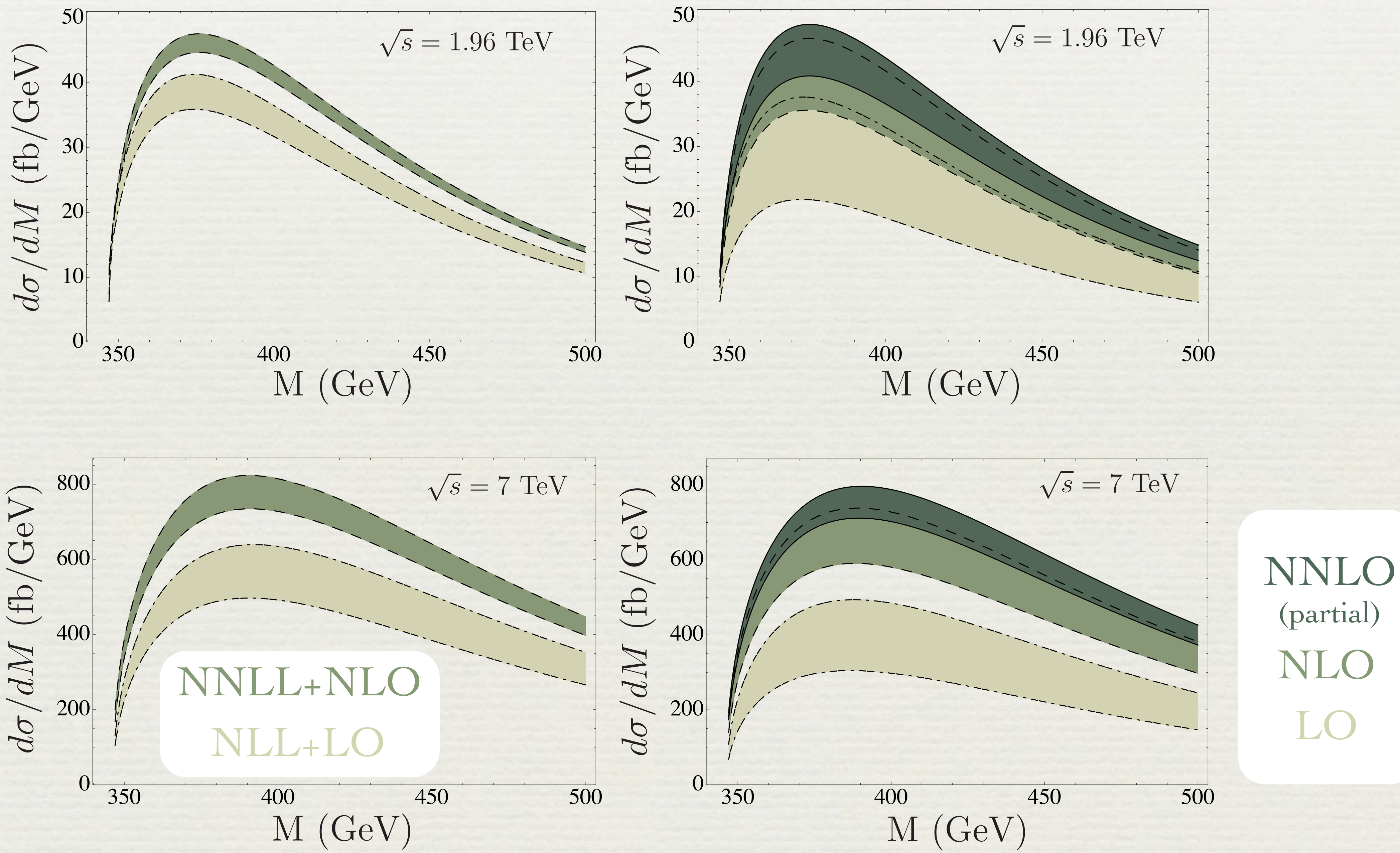


Threshold resummation at NNLL

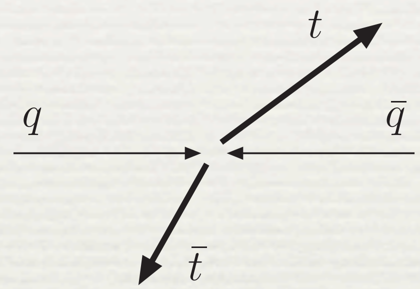
Ahrens, Ferroglia, MN, Pecjak, Yang: in prep.

- Resum, lower LHC energy, change colors...

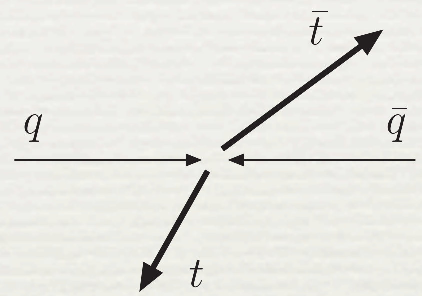


Forward-backward asymmetry

- At Tevatron, top-quark are emitted preferably in direction of incoming quark



Preferred



Suppressed

- Define inclusive asymmetry:

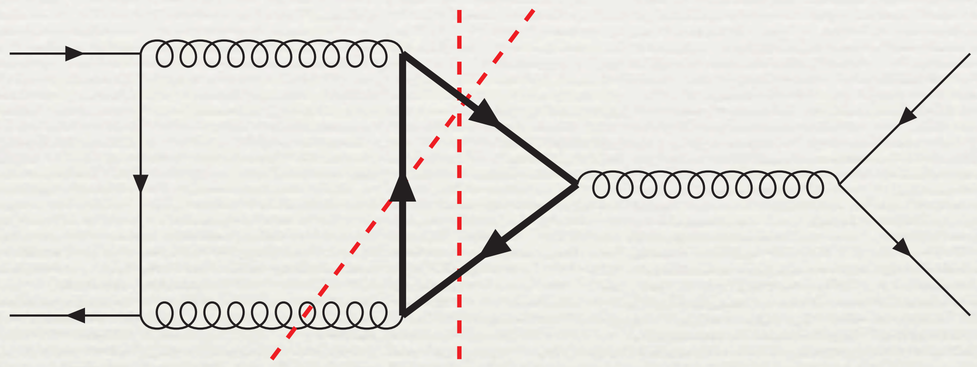
$$A^t_{\mathrm{FB}} \equiv \frac{\int_{4m_t^2}^{s} dM \left(\int_0^1 d\cos\theta \frac{d^2\sigma^{N_1 N_2 \to t\bar{t}X}}{dM\, d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d^2\sigma^{N_1 N_2 \to t\bar{t}X}}{dM\, d\cos\theta} \right)}{\int_{4m_t^2}^{s} dM \left(\int_0^1 d\cos\theta \frac{d^2\sigma^{N_1 N_2 \to t\bar{t}X}}{dM\, d\cos\theta} + \int_{-1}^0 d\cos\theta \frac{d^2\sigma^{N_1 N_2 \to t\bar{t}X}}{dM\, d\cos\theta} \right)}$$

- Surprising result by CDF:

$$A_{FB}^{t}\,|_{exp} = (19.3 \pm 6.9)\%$$

Forward-backward asymmetry

- Non-zero contributions arise first at one-loop order, from interference terms such as:



- Predictions:

fixed-order

$$A_{\rm FB}^t\Big|_{\rm NLO}^{\rm FO} = 5.1^{+0.7}_{-0.6}\,\% \qquad (M/2 \le \mu \le 2M)$$

$$A_{\rm FB}^t\Big|_{\rm NLO}^{\rm FO} = 6.2^{+0.5}_{-0.7}\,\% \qquad (m_t/2 \le \mu \le 2m_t)$$

Kühn, Rodrigo 1998

resummed

$$A_{\rm FB}^t\Big|_{\rm NLL}^{\rm RES} = 5.7^{+3.2}_{-3.1}\,\%$$

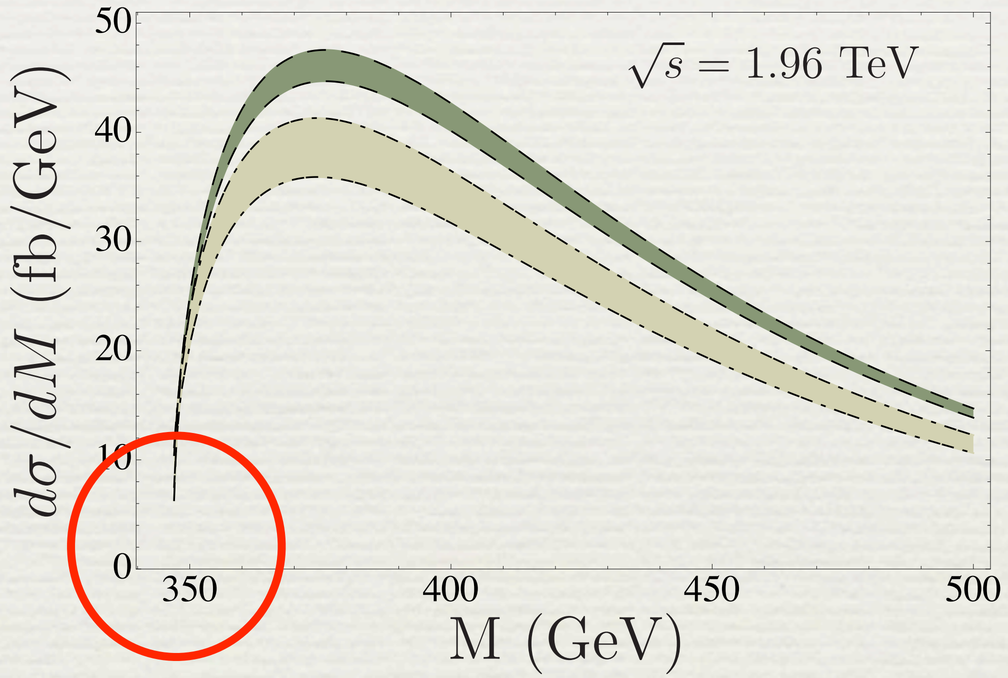
Almeida, Sterman, Vogelsang 2008

$$\boxed{A_{\rm FB}^t\Big|_{\rm NNLL}^{\rm RES} = 5.8^{+0.8}_{-0.8}\,\%}$$

this work!

Total cross section

- Computed at NLO already in 1988
- Usually, resummation is done around partonic threshold at $\hat{s}=4m_t^2$
- Combined Coulomb and soft gluon resummation for $\beta_{tt} \to 0$
- In our approach, soft gluon effects are resummed also far above threshold (more important at higher M)
- Different systematics!



Total cross section

- Main effect of resummation is to stabilize scale dependence
- β_{tt} expansion misses important contributions

Cross section (pb)	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
σ_{LO}	$5.25^{+2.07+0.30}_{-1.36-0.22}$	102^{+36+5}_{-24-5}	256^{+81+11}_{-57-11}	$563^{+160+20}_{-112-19}$
σ_{NLL}	$5.05^{+0.38+0.26}_{-0.35-0.20}$	98^{+15+5}_{-14-5}	241^{+41+10}_{-31-10}	521^{+95+19}_{-73-16}
$\sigma_{\mathrm{NLO_{thresh}}}$	$6.20^{+0.39+0.31}_{-0.71-0.23}$	$144^{+5\ +7}_{-13-8}$	360^{+10+14}_{-29-17}	791^{+15+27}_{-54-30}
σ_{NLO}	$6.49^{+0.33+0.33}_{-0.70-0.24}$	150^{+18+8}_{-19-9}	379^{+45+17}_{-46-17}	841^{+97+31}_{-97-30}
$\sigma_{\mathrm{NNLL+NLO}}$	$6.48^{+0.17+0.32}_{-0.21-0.25}$	146^{+7+8}_{-7-8}	368^{+20+19}_{-14-15}	813^{+50+30}_{-36-35}
$\sigma_{\mathrm{NNLO,\,approx}}$ (scheme A)	$6.72^{+0.45+0.33}_{-0.47-0.24}$	162^{+19+9}_{-14-9}	411^{+49+17}_{-35-20}	$911^{+111+35}_{-77\ -32}$
$\sigma_{\mathrm{NNLO,\,approx}}$ (scheme B)	$6.55^{+0.32+0.33}_{-0.41-0.24}$	$149^{+10+8}_{-9\ -8}$	377^{+28+16}_{-23-18}	832^{+65+31}_{-50-29}
$\sigma_{\mathrm{NNLO,}\,\beta-\mathrm{exp.}}$	$7.24^{+0.13+0.36}_{-0.31-0.27}$	158^{+1+8}_{-1-9}	396^{+5+17}_{-2-18}	$871^{+16+31}_{-3\ -33}$
$\sigma_{\mathrm{NNLO,}\,\beta-\mathrm{exp.+\,potential}}$	$7.13^{+0.17+0.36}_{-0.38-0.26}$	162^{+3+8}_{-3-9}	$407^{+11+17}_{-6\ -18}$	895^{+30+31}_{-12-33}

scale uncertainty

PDF uncertainty

Conclusions

- Effective field theory provides efficient tools for addressing important, difficult collider-physics problems
- Systematic "derivation" of factorization theorems (known ones and ones to be discovered) and simple, transparent resummation techniques based on anomalous dimensions
- Nontrivial applications exist for Drell-Yan, Higgs production, and top-quark pair production
- Long-term goal is an automatized implementation of resummation at NNLL/NLO order for jet processes such as pp→n jets+V/H at LHC (with $n \leq 3$, $V = \gamma, Z, W$)